

## Probing Dark Matter

by Adam Burrows and James Liebert

Recent novel observations have probed the baryonic fraction of the galactic dark matter that has eluded astronomers for decades. Late in 1993, the MACHO<sup>1</sup> and EROS<sup>2</sup> collaborations announced in this journal the detection of transient and achromatic brightenings of a handful of stars in the Large Magellanic Cloud (LMC) that are best interpreted as gravitational microlensing<sup>3</sup> by low-mass foreground objects (MAssive Compact Halo Objects, “MACHOs”). This tantalized astronomers, for it implied that the population of cool, compact objects these lenses represent could be the elusive dark matter of our galactic halo. A year later in 1994, Sackett *et. al*<sup>4</sup> reported the discovery of a red halo in the galaxy NGC 5907 that seems to follow the inferred radial distribution of its dark matter. This suggested that dwarf stars could constitute its missing component. Since NGC 5907 is similar to the Milky Way in type and radius, some surmised that the solution of the galactic dark matter problem was an abundance of ordinary low-mass stars.

Now Bahcall *et. al*<sup>5</sup>, using the Wide-Field Camera of the recently repaired Hubble Space Telescope, have dashed this hope. In a letter to the *Astrophysical Journal*, they report the results of a deep pencil-beam search in the V and I spectral bands for red dwarfs in our galaxy. Surveying a high-latitude patch of the sky 4.4 square arcminutes in area, Bahcall *et. al* find very few such stars and conclude that red dwarfs above the stellar edge can contribute no more than 6% to the mass of our dark halo and no more than 15% to the mass of the galactic disk. One intriguing consequence of this observation is that if the microlenses are not in the LMC itself<sup>6</sup> and the halo is indeed made of MACHOs, they are not stars above the hydrogen-burning limit, but brown dwarfs below it. However, if the MACHOs are not the dark matter, then the results of Bahcall *et. al* imply that the missing galactic mass has a particle-physics solution. Either way, the scientific community has recently accelerated its search for the dominant component of the galaxy.

What distinguishes the HST observations of Bahcall *et. al* is that they were done

from space with unmatched angular resolution. Resolutions of  $\sim 0.1$  arcseconds allow astronomers to discriminate between point dwarf stars and the extended galaxies that dominate a field deeper than  $\sim 21$  magnitudes in the visible. Since competitive pencil-beam surveys are at least five magnitudes deeper than this, it is generally thought that one must be able to separate stars from galaxies to obtain a credible red star census. However, few extragalactic objects intrude on the color range of the low mass Population II stars (subdwarfs). In studies of this population, the star-galaxy separation problem is moot. It is appropriate, then, to ask how well the HST result agrees with Pop II studies made from the ground?

Dahn *et. al*<sup>7</sup> have recently estimated the luminosity function (LF) of a kinematically-selected sample of Pop II (visible spheroid) stars in the solar neighborhood. Most of the stars in their sample had trigonometric parallaxes (and, hence, directly-measured distances), a feature that deep pencil-beam surveys lack. The Dahn *et. al* LF peaks sharply near  $M_V = 12$  ( $M_I = 10$ ) and turns downward towards an apparent terminus near  $M_V = 14$ - $14.5$  ( $M_I = 11$ ). They concluded that the subdwarfs from the halo comprise only about 1/1000'th of the mass in stars in the solar neighborhood – approximately what Bahcall *et. al* derive from space. If we extrapolate the Dahn *et. al* LF to the HST field and assume that the Galactic density goes as  $R^{-3.5}$  for the visible spheroid, we predict what Bahcall *et. al* in fact saw: only a handful of stars. However, if this LF were applied to a baryonic “dark halo” with a local density of 0.009 solar masses per cubic parsec<sup>8</sup> and an  $R^{-2}$  density dependence, then upwards of 60 stars should have appeared in the HST field (as Bahcall *et. al* point out).

Deep ground-based pencil-beam surveys have pushed the CCD detector state-of-the-art to fainter magnitudes, using telescopes larger in aperture than the HST and covering larger areas of the sky. Particularly important have been the surveys of Tyson<sup>9</sup>, Hu *et. al*<sup>10</sup>, and Boeshaar, Tyson, and Bernstein<sup>11</sup>. These workers probed larger volumes of space than Bahcall *et. al* and estimated Pop II low mass star densities consistent with both the Bahcall

*et. al* and Dahn *et. al* results. The only LF inconsistent with these ground-based studies and the HST study is that Richer and Fahlman<sup>12</sup>, whose LF is rising sharply down to the main sequence limit.

The dearth of edge stars, either dwarfs or low-metallicity subdwarfs, allows us to conclude with some certainty that neither red dwarfs nor subdwarfs can be a major mass fraction of any component of the galaxy. We are left with a classic mystery: we think that there are compact microlenses between us and the LMC, but we can not see them directly with our best cameras. Furthermore, if they are old brown dwarfs, we can not explain why they were formed as a distinct population that is not a simple extrapolation of the stars that we do see.

These novel surveys demonstrate just how great has been the recent improvement in search technology. Deep pencil-beam surveys have the potential to provide new and important data on the nature of the galactic halo (and what it can not be) that will complement those now being obtained by the microlensing searches sensitive only to gravitational mass. All too often, discussions of the halo dark matter have resembled medieval discourses on the Aristotelean quintessence or the angelic population of the empyrean. Astronomers seemed to be involved in bootless shadow boxing with a Nature jealous of its secrets. With the recent deep photometric and microlensing surveys, we may finally be learning something of substance concerning the dominant constituents of our galaxy and, perhaps, the universe.

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## References

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